Design and Implementation of a Self-configuring Ad-hoc Network for Unmanned Aerial Systems

H. Claus Christmann* and Eric N. Johnson†

Georgia Institute of Technology, Atlanta, Georgia, 30332, USA

Unmanned aerial vehicles (UAVs), and unmanned aerial systems (UAS) as such in general, need wireless networks in order to communicate. UAS are very flexible and hence allow for a wide range of missions by means of utilizing different UAVs according to the mission requirements. Each of these missions also poses special needs and requirements on the communication network. Especially, mission scenarios calling for UAV swarms increase the complexity and call for specialized communication solutions.

This work focuses on these specialties and needs and describes the selection process, adaptation and implementation of an ad-hoc routing protocol tailored to an UAV surrounding and a correspondingly adapted communication method.

I. Introduction

Currently there is ongoing research in the field of mobile ad-hoc networks (MANET) for several scenarios. The main interest is in application for traffic scenarios, mobile phone systems, sensor networks and future combat systems. Recent research has focused on topology related problems such as range optimization, routing mechanisms, or address systems, as well as security issues like traceability or encryption. In addition, there are very specific research interests such as the effects of directional antennas for MANETs and minimal power consumption for sensor networks. Most of this research aims either at a general approach to wireless networks in a broad setting or focuses on an extremely specific issue.

UAS have specific needs not provided by the general research, but are, on the other hand, too diversified to make use of all the narrowly focused developments; thus, UAS form a sufficiently large area of application of MANETs to be considered as an independent group with specialized needs worthy of specifically tailored implementations of MANET principals.

Even though a vast amount of MANET protocols have been proposed[a], research has not tackled a general approach to UAS, although some papers show specific applications involving UAVs.[1] This work tries to approach this gap. By specifying mission scenarios for UAVswhich are utilizing a swarm of UAVs, the aim is to generate a representative cross section of current UAS applications. The scenarios should cover research scenarios, i.e. research institutes operating their vehicles, as well as civil search and rescue or disaster observation scenarios, or military missions. The scenarios are modeled for medium sized vehicles and their according abilities. The Georgia Institute of Technology UAV Research Facility (GT UAV RF) operates 10-15lbs MTOW helicopters which were used as a representative example.

First this paper describes the generated evaluation scenarios. Different MANET protocols are then evaluated in these scenarios (by means of a simulation in the network simulator `ns-2`) in order to find a routing protocol that handles the proposed requirements appropriately and hence would be recommended for implementation. Finally the findings are presented and discussed.

*Graduate Research Assistant, Daniel Guggenheim School of Aerospace Engineering, 270 Ferst Drive, Atlanta, GA 30332-150, AIAA Student Member

†Lockheed Martin Associate Professor of Avionics Integration, Daniel Guggenheim School of Aerospace Engineering, 270 Ferst Drive, Atlanta, GA 30332-150, AIAA Member

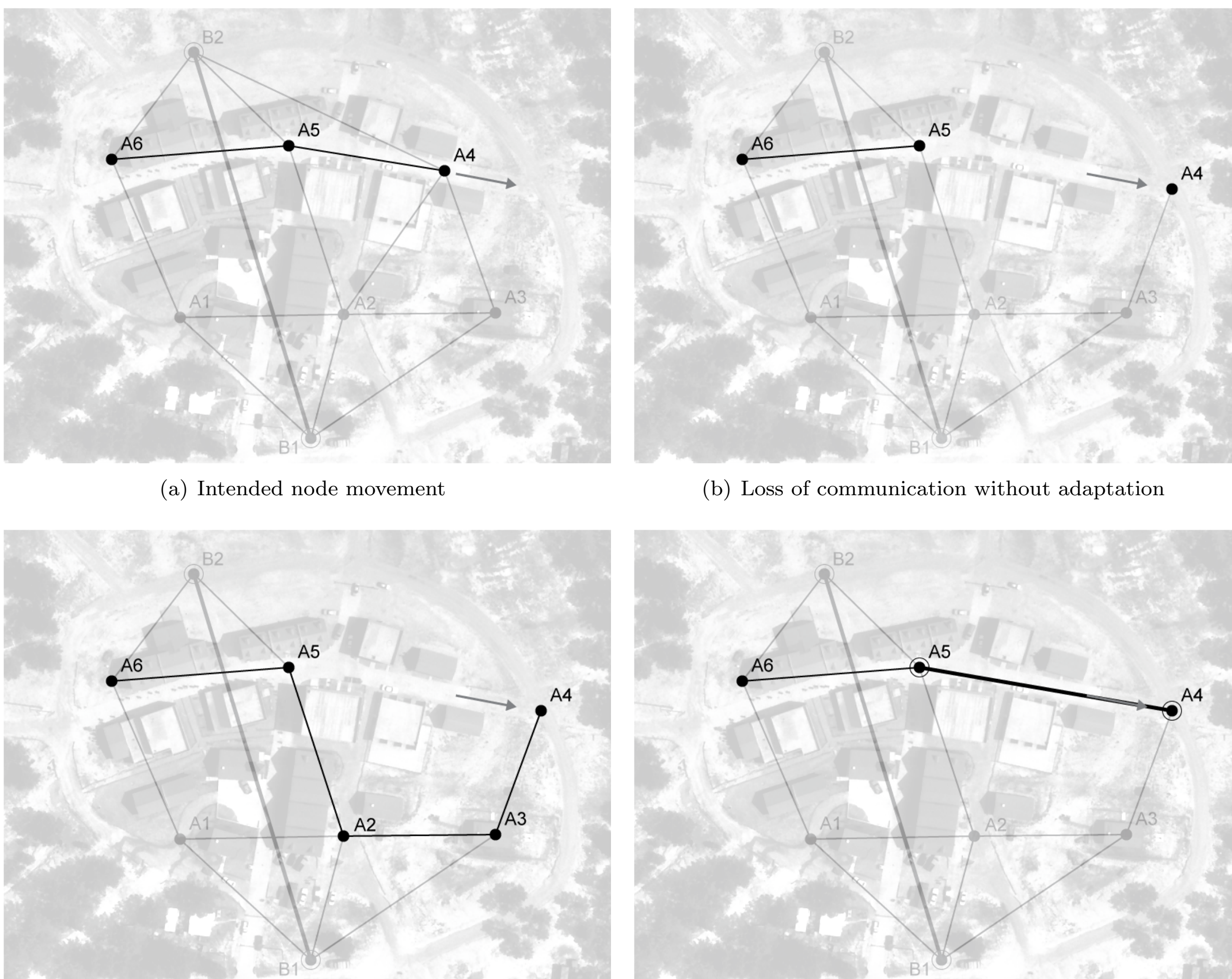
[a] `http://en.wikipedia.org/wiki/Ad_hoc_routing_protocol_list` lists nearly 100 ad-hoc routing protocols.

II. Definition of Evaluation Scenarios

As pointed out above, the connection to real applications heavily depends on how realistic the evaluation scenarios are. In those scenarios the different members of a UAS the ground control station and the UAVs, represent the nodes of the network and internal data as well as external sensor information needs to be passed around, especially to the ground control station operator.

It can be easily seen that, dependent on the type of network, i.e. the density of nodes, the average speed of motion of the nodes, the motion behavior, etc., different network protocols and their protocols to establish a route, will behave and perform very differently. One of the main issues here is the problem of routing packets through the always changing physical topology of the network and how the communication methods adapt the network topology to that. Related problems, such as loss-of-link (LoL), are also a major concern here. Fig. 1 gives a generic picture of routing problem.

This leads to the initial problem of evaluating network protocol performance measures and comparing them, because the performance of networks depends on the topology (and the topology changes over time) of the network. Finding a representative network setup is one of the major challanges in the whole process of finding an appropriate protocol. Due to the nature of the network participants, UAVs, the physical topology changes since its members are not only able to, but will, move and hence the relative position between them changes.



(a) Intended node movement

(b) Loss of communication without adaptation

(c) Counter reaction based on rerouting

(d) Counter reaction based on changing the transmission devices

Figure 1. The network should also be able to handle the on-the-fly changes by means of reconfiguration. The apparent way would be to rely on the routing algorithms, but since UAVs might have redundant communication devices the switch to a device with different propagation properties could be a better solution.

Based upon the general problem of how to reach a certain node in a network, three evaluation scenarios have been created. The common base among all of the created scenarios is the intent to find a representative cross section able to mimic network scenario situations appearing in real missions. The three scenarios (Fig. 2) are outlined next.

A. Non-Intrusive Surveillance

The first scenario, Fig. 2(a), covers problems of partial reachability and constant rerouting. In this scenario the UAS is tasked survey an area of interest by means of continuous video surveillance.

The mission scenario proceeds as follows: the swarm of 8 UAVs progresses to the area of interest in formation, reaches a detachment point and deploys its swarm members one at a time. Here one UAV stays behind halfway to the area of interest and one stays at the detachment point. In this scenario 6 UAVs are then deployed from the detachment point in such a way that they are equally spaced on the surveillance loop path, indicated in Fig. 2(a) by $\diamondsuit$. After the deployed UAVs have finished a given number of surveillance loops they regroup with the main UAVs and head back to the starting point. During the whole mission the ground control station is stationary, indicated by an `x`.

The scenario requires the network protocol to adapt to a constantly changing topology. The ground control station is able to establish a link by means of the two main UAVs, left behind stationary in order to maintain link by forwarding packets. The deployed UAVs are able to maintain their relative order and hence their network topology throughout their motion pattern. The first deployed UAV is always followed by the second (and so forth), but the connection to the ground control station via the main UAVs is constantly handed over to a different UAV in a repetitive way.

B. Expanding Search

The second scenario, Fig. 2(b), covers the problem of a constant increase in the numbers of hops a packet has to take in order to reach its destination.

Similar to the non-intrusive surveillance scenario, the swarm ingresses in formation up to a detach point close to the area of interest. While doing this, one UAV is left behind as a relay station, another one stays at the detachment point. From here 6 UAV then approach the area of interest still in formation. Whenever the formation reaches a fork a split is performed and each group continues. Entering the area of interest from the west the swarm quickly splits up into single UAVs, performing a complete search of the city. When done, each UAV holds at the perimeter of the area of interest waiting for the other UAVs to finish their search branch. After that all UAVs regroup at the detachment point and return to the ground control station.

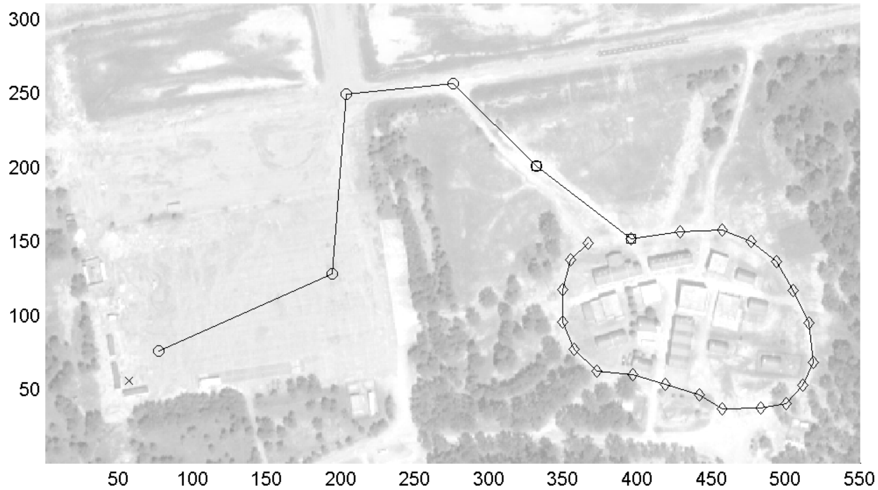
Similar to the physical paths of the different UAVs the network is tasked to keep track of the continuously branching topology and reroute the packets accordingly.

C. Coordinated Approach

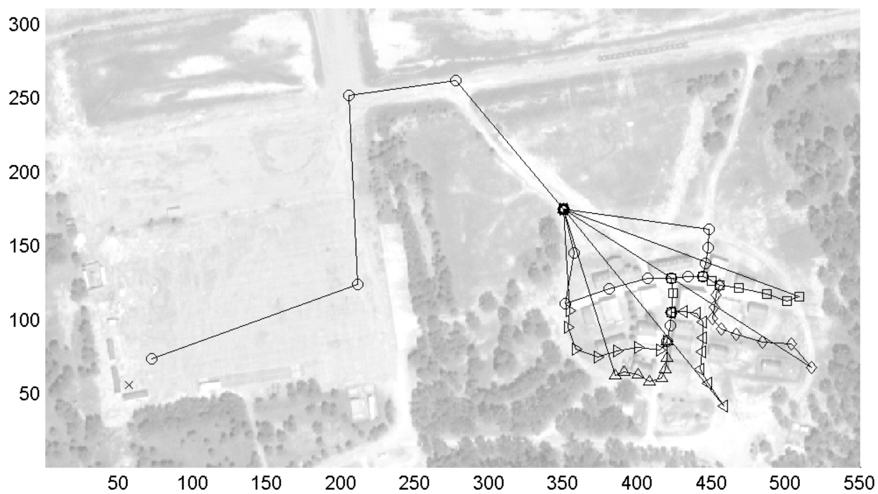
The third scenario, Fig. 2(c), is tailored to a more bandwidth oriented problem since during the mission the possibility for a bandwidth bottleneck arises.

In this scenario the swarm approaches the area of interest, leaving one relaying UAV behind. But unlike in the other two scenarios a first major split happens away from the area of interest. Both groups then approach from different angles. Once in the vicinity of the area of interest, one UAV is again left behind for relay purposes, the others acquiring a holding position on the perimeter. Once all UAVs have reached their approach locations, all of them engage in a coordinated fashion towards a single point of interest. After surveying this for a given amount of time the UAVs around the point of interest regroup and leave the area of interest in formation. Outside the area of interest they regroup with the UAVs left behind for relay purposes and head back to the ground control station.

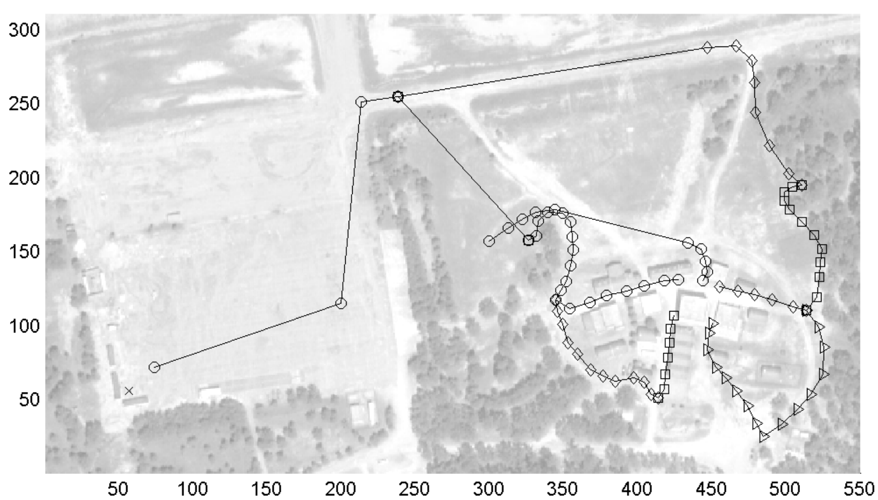
Due to the early split into two groups all network traffic from the group further away from the ground control station has to be routed through the closer group. Also the network is spread out, possibly allowing for a loss-of-link situation. The network is tasked to schedule traffic in order to avoid dropping to many packets at possible bandwidth bottlenecks.



(a) Non-Intrusive Surveillance



(b) Expanding Search Pattern



(c) Coordinated Approach

Figure 2. Three evaluation scenarios are used to mimic common problems of MANETs. These are mainly the problems of partitioning, i.e. detaching from the network, and reachability, i.e. routing.

III. Network Related Scenario Requirements

After identifying each evaluation scenario, a quick overview about network related challenges is already given in the previous section. It is of interest to know if and how a scenario and the related motion pattern poses different weights on the general requirements of the communication method or if there are also special requirements arising from individual scenarios. Requirements on the network here mean, for example, bounds on maximum latency or minimum bandwidth. Furthermore special requirements for a scenario, for example a bound on the power used by a transmission device, could be used to appropriately adapt the network communication. This might be true for example for the coordinated approach scenario, picturing it as a support mission for a military assault team. Here less emitted radio energy would result in a smaller chance to be detected.

A. Basic Communication with the Ground Control Station

During all of the above missions one given requirement is to maintain an overview about the mission by sending constant updates about the status of the UAVsin the swarm back to the ground control station.

In order to accomplish this, two data streams are introduced: a fast and short one and a slightly slower but more rigorous status report. The first is assumed to be 68 bytes at a rate of 10Hz, the second to be 184 bytes at 1Hz[b].

In addition to this datalink the sensor information needs to be transmitted to the ground control station. This is assumed to be a 300kbit/s video stream[c].

B. Special Scenario Requirements

In order to impose different bandwidth needs the following requirements are imposed on the scenarios.

For the expanding search high resolution imagery is required, being taken ever so often in order to map the area of interest. This is reflected by simulating high resolution pictures for any point of interest, which is approximated to be a 2MB[d] traffic every 10s.

The coordinated approach represents a different kind of mission where a high priority is given to data about the point of interest. Hence no extra traffic is added until the UAVs reach the point of interest. Then the video stream above is changed and a 1Mbit/s stream replaces the 300kbit/s stream until the UAVs leave the point of interest and the slower stream is activated again. This intends to mimic a higher quality sensor that has some other penalties (e.g. a higher power consumption) so that it cannot be used at all times.

Nothing is added to the non-intrusive surveillance scenario.

IV. Selection of Promising Candidates

Since the focus of this work is the special requirements for UAS and the implementation of a correspondingly adapted communication method, it is not intended to develop a new protocol, but merely to make use of techniques already developed.

So far a combination of different proposed protocols (e.g.[2][3][4]) seemed to match the list of requirements better than a single protocol. This idea was fostered by the thought that geographic routing algorithms seemed to be perfectly suitable for applications involving UAS, but evaluating the given scenarios with the classic ad-hoc network protocols DSR,[5] DSDV,[6] TORA,[7] and AODV,[8] which are already available in the network simulator package `ns-2`,[9] revealed different results.

V. Evaluation of the Preselected Protocols

The network simulator `ns-2` was used in order to evaluate the routing protocols. So far research made use of network scenarios with large amounts of nodes and mostly a random motion pattern in a constrained area. Some research focusses on MANETs for application in vehicles and hence the mobility of the nodes is constrained to a mostly "urban" motion, i.e. moving in corridors, representing streets.

---

[b]These are modeled after datalink messages used by the GT UAV RF.

[c]300kbit/s represents a common "high bandwidth" video stream that, if utilizing appropriate compression algorithms, satisfies quality requirements for non high-resolution live video.

[d]This mimics a 5 mega pixel picture at moderate compression.

The authors of this work were interested in a very special application of UAS build from a single ground control station and up to 10 medium sized UAV. This setup is believed to be a realistic model for UAV swarm applications currently being used. Hence the evaluation scenarios were special and very constrained if compared to the large area, random node motion scenarios. As a result of this the number of nodes is very limited (all of the evaluation scenarios require less than 10 nodes) and the operational area is very small also, considering the available transmission power[e].

As a result of this, the simulation showed that the performance of the current wireless network hardware is more than sufficient for the demands outlined in the evaluation scenarios. The mentioned routing protocols performed as described but in order to make use of their route detection and route maintenance routines the used transmission power had to be dropped quite a bit. Hence any performance difference resulting from the different protocols disappeared.

VI. Discussion of Results and Conclusion

The overall result of this work is the fact, that even though UAS are highly specialized and in the need for MANETs, specialized routing protocols are currently not necessary.

The evaluation scenarios reflect a realistic UAS including several, but not many, UAV. As outlined in the motivation for the DREAM[10] protocol, network routes changes happen more often in cases where the relative position of the nodes changes frequently, i.e. when the nodes are close.

Porting this to UAS would require several UAVs to operate close enough to be in range of each other and at the same time moving around relative to each other, but also far enough apart to not be able to reach nearly everybody in the swarm. None of this can be found in the presented evaluation scenarios, which intended to mimic current UAS applications, i.e. a limited amount of UAVs in a confined area. In cases when the area is increased, the scenario is expected to change to a long time surveillance mission. Currently this requires rather large UAV which in return have extended surveillance capabilities. Hence only a few would be used which eliminated the need for advanced route discovery algorithms.

Increasing the number of UAV involved in the network would result in the need for route discovery algorithms. At this time networks of more than 10 or 20 UAV seem to be the exception rather then the rule.

Since the authors are specifically interested in applications of UAS as outlined, the conclusion is that network management inside the network protocol itself is not necessary. The authors propose to establish a regular 802.11b/g network and shift any kind of routing decision into higher application levels, which would allow a more integrated approach to the problem.

VII. Future Work

This integrated approach has to be examined. One point of interest is the usage of diverse link systems within the network and to manage UAV swarms with WiFi as well as serial data links. This would allow for scenarios as pictured in Fig. 1(d), but with the difference that slower and longer range links would not be a possible fall back option but the only present link.

Also of interest is to introduce line of sight only connections, e.g. urban canyons. This clearly requires a higher level of control since the capability of maintaining link directly results from the geographical position of the UAV, hence a connection of physical motion and network demands is necessary.

References

[1] Brown, A. S. and Carter, D., "Geolocation of Unmanned Aerial Vehicles in GPS-Degraded Environments," 26 - 29 September 2005 2005, AIAA-2005-7011.

[2] Shen, C.-C. and Jaikaeo, C., "Ad hoc multicast routing algorithm with swarm intelligence," *Mobile Networks and Applications*, Vol. 10, No. 1-2, 2005, pp. 47–59.

[3] Li, J., Jannotti, J., Couto, D. S. J. D., Karger, D. R., and Morris, R., "A scalable location service for geographic ad hoc routing," *Proceedings on the 6th annual international conference on Mobile computing and networking*, ACM Press, Boston, Massachusetts, United States, 2000, pp. 120–130.

[4] Lee, S., Bhattacharjee, B., and Banerjee, S., "Efficient geographic routing in multihop wireless networks," *Proceedings on the 6th ACM international symposium on Mobile ad hoc networking and computing*, ACM Press, Urbana-Champaign, IL, USA, 2005, pp. 230–241.

[e] IEEE 802.11b/g generally allows for 100mW, depending upon the location up to 1W can be allowed

[5]Johnson, D. B. and Maltz, D. A., "Dynamic Source Routing in Ad Hoc Wireless Networks," *Mobile Computing*, edited by Imielinski and Korth, Vol. 353, Kluwer Academic Publishers, 1996.

[6]Perkins, C. and Bhagwat, P., "Highly Dynamic Destination-Sequenced Distance-Vector Routing (DSDV) for Mobile Computers," *ACM SIGCOMM'94 Conference on Communications Architectures, Protocols and Applications*, 1994, pp. 234–244.

[7]Park, V. D. and Corson, M. S., "A Highly Adaptive Distributed Routing Algorithm for Mobile Wireless Networks," *INFOCOM (3)*, 1997, pp. 1405–1413.

[8]Perkins, C., "Ad Hoc On Demand Distance Vector (AODV) Routing," 1997.

[9](http://nsnam.isi.edu/nsnam/index.php), "The Network Simulator - ns-2," .

[10]Stefano, B., Imrich, C., Violet, R. S., and Barry, A. W., "A distance routing effect algorithm for mobility (DREAM)," *Proceedings on the 4th annual ACM/IEEE international conference on Mobile computing and networking*, ACM Press; New York, NY, USA, Dallas, Texas, USA, 1998, pp. 76–84.